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AN ANALOG-DIGITAL SYSTEM FOR DISCRIMIN-
ATORY EXHAUST GAS SAMPLING

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AUTOMOTIVE SAFETY RESEARCH PROGRAM

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Pennsylvania Transportation and Traffic Safety Center

Report No. 28

AN ANALOG-DIGITAL SYSTEM FOR
DISCRIMINATORY EXHAUST GAS SAMPLING

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July, 1968

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ABSTRACT

Cycle-to-cycle variations of the combustion process of spark ignition engines, usually observed as peak pressure variations, are a well-known phenomenon whose causes have not yet been identified with certainty. The variations decrease power and efficiency and may, as has recently been postulated, also impose a lower limit on exhaust emission reduction.

For investigating whether or not there is a relationship between physical cycle characteristics, such as peak pressure, and exhaust gas composition a sampling system was developed which collects bag samples from specified cycles only. It consists of an analog portion for obtaining pressure and rate-of-pressure change signals, a digital logic portion for discriminating between signals according to selected criteria, and an electrically actuated sampling valve in the engine exhaust system. Since signal analysis and discrimination are instantaneous, gas sampling is done during the exhaust stroke of the same cycle for which the logic generated the command to sample.

The system is described in detail, its use is explained, but no engine results are included in this report.

ACKNOWLEDGMENTS

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The opinions, findings and conclusions of this report are those of the authors and not necessarily those of the U. S. Public Health Service.

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NOTATIONS

	Symbols	Units
Constants	A, B, K, S	-
Variables	x, y	-
Time	τ	sec
Pressure	p	lb/in ²
Rate of Pressure Change	dp/d τ	lb/in ² sec
Engine Speed	N	rpm
Angle	ϕ	deg
Crank Angle	-	deg CA
Frequency	f	Hz
Angular Velocity	ω	radian/sec
Gain	G	-
Resistance	R	Ω - Ohm
Capacitance	C	F - Farad
Inductance	L	h - Henry
Voltage	V, e	v - Volt
Current	i	amp - Ampere
Charge	Q	coulomb
Imaginary Number	j	-
Unity Gain Bandwidth	f _u	Hz

Prefixes	Magnitude
p = pico	10^{-12}
n = nano	10^{-9}
μ = micro	10^{-6}
m = milli	10^{-3}
k = kilo	10^3
M = mega	10^6

Chapter 1

INTRODUCTION

General Statement of the Problem

For some time past it has been observed that piston engines of the spark ignition type display wide variations in the combustion process as indicated, e.g., by the pressure development from one cycle to another. These random variations occur although overall engine operating conditions are apparently kept constant. The engine's mechanical (power output) and chemical (exhaust gas emissions) performance are the result of an averaging out of the individual cycles. It has been suggested that if the variations are large the results will be reduced power and economy and increased undesirable exhaust gas emissions. If so, then it would be desirable to eliminate cycle-to-cycle variations. As a first step, therefore, the work of which this thesis is a part is directed toward achieving a better understanding of the variations in the combustion process.

One of the points in question is the existence of a correlation between the random variations of the combustion process and the exhaust gas emission. Depending on the existence and nature of such a relationship, a solution to the exhaust emission problem might then be attempted by decreasing the magnitude of the variations. However, in order to establish the relationship it is necessary to design a system capable of correlating certain parameters of the combustion process.

with the resulting exhaust products from individual engine cycles.

The design of such a system is the objective of this thesis.

Previous Work

Random variation of the combustion process affecting the pressure development in the cylinder of an I.C. engine has been studied by Vichnievsky and co-workers (1),¹ (2), Soltau (3), Patterson (7) and Karim (9). Curry (4), (5), Harrow and co-workers (6), and Warren and Hinkamp (8) have investigated the cyclic dispersion of the flame propagation. Most authors tried to isolate the causes of irregularity by a process of elimination; conclusive proof for any one cause has not yet been found. Vichnievsky and co-workers observed that cyclic dispersion was present under all operating conditions with many fuels; the use of a shroud on the inlet valve markedly reduced the extent of variation. Soltau examined the variation in the cylinder maximum pressure with changes of most common engine variables. The air fuel ratio was the main factor which influenced the magnitude of the maximum pressure variation. He concluded that any measures that produce rapid burning will usually produce steadier pressure development. Patterson postulated that the major causes of combustion rate variation are the mixture velocity differences that exist within the cylinder near the spark plug at the time of ignition. He proposes that an increase of the average combustion rate, achieved by better design of intake manifold and valve, will reduce pressure variations. Karim's findings are similar to those of Soltau; he also observed that the small variation

¹ Numbers refer to entries in the Reference list on p. 49.

in the ignition timing of the normal spark has little contribution to the dispersion.

Curry investigated the combustion process in a spark ignition engine in terms of flame development and subsequent propagation throughout the combustion chamber. He found that variations in the ignition process do not appear to be the cause of cycle-to-cycle variations in the time required to complete the combustion; the reaction propagates immediately from the spark and is quite repeatable. Variations in combustion time are caused by appreciable differences in flame propagation rates. These differences, becoming apparent quite early in the flame front development, control the subsequent overall combustion time. Harrow found that the extent of cycle-to-cycle variation in flame travel time depends to a large degree on the fuel used. Warren and Hinkamp showed that the minimum dispersion in flame front travel time occurred at an ignition setting close to that for maximum power.

None of the workers mentioned has attempted a statistical analysis of the cycle-to-cycle exhaust gas composition and its correlation with other engine parameters, and it does not appear to have been done elsewhere.

Within the frame of this work falls a paper by Ohigashi and co-workers (10), where a digital conversion method for the statistical evaluation of engine performance is described. A great number of publications exist on cylinder pressure measurement and its error; references are listed e.g. by Brown (11).

Specific Objective

For the cycle-to-cycle study of the combustion process in a spark ignition engine it is desirable to know whether a relationship exists between the physical characteristics such as cylinder pressure and the exhaust gas composition of individual cycles. The objective of this work then is to devise and build a system that is capable of providing exhaust gas samples from individual engine cycles selected on the basis of the occurrence during the cycle of certain physical characteristics. Fig. 1 shows the system to be designed and the signal flow from the engine pressure transducer to the discriminator and from there to the sampling valve in the exhaust pipe.

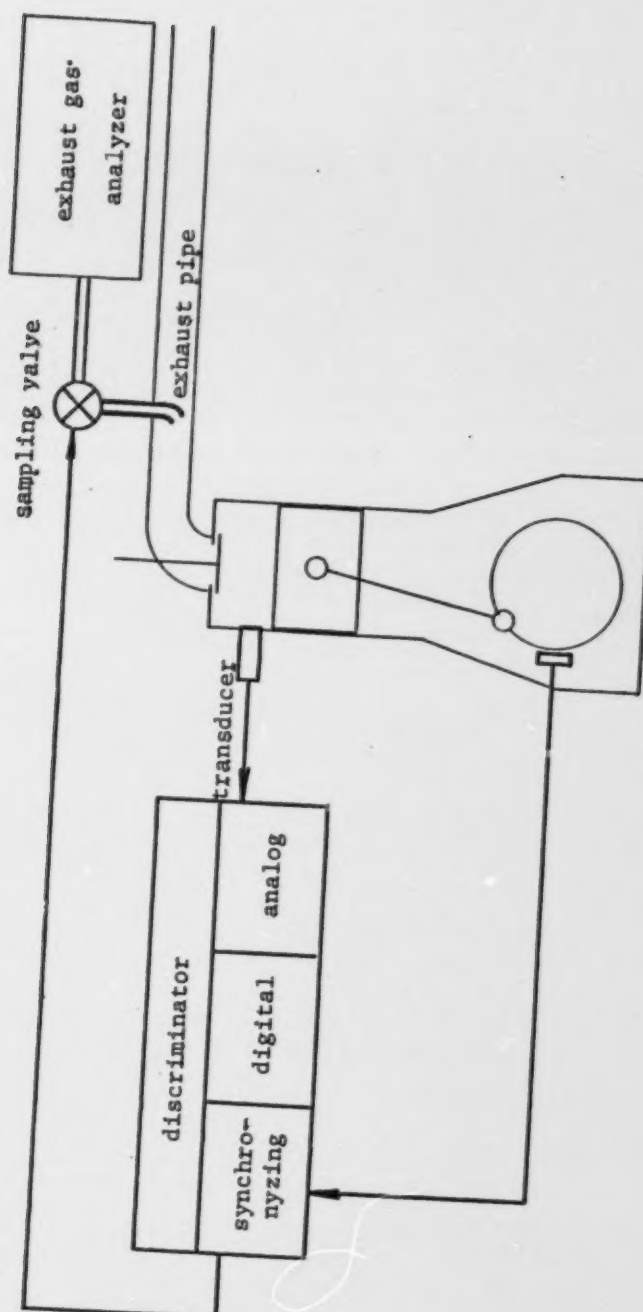


Figure 1. System components and signal flow

Chapter II

DEVELOPMENT OF THE DESIGN CRITERIA

Measured Parameters

The overall goal of the study, of which this thesis is a part, is to establish a correlation between some physical characteristics during the combustion process and the exhaust gas analysis of individual engine cycles. The present thesis is not concerned with the chemical analysis of the exhaust gas. The criteria for the physical parameters which define the selected samples are that they must be characteristic of the combustion process, independent of each other (if more than one is used at a time) and that they can be measured instantaneously. Additionally, since the physical characteristics are functions of time, specified values in the cycle will have to be picked, e.g., most of the previous statistical analysis has been done using peak values in the cycle.

Pressure and rate of pressure rise in the cylinder have always been considered characteristic functions of the combustion process. Another useful characteristic might be the work of the cycle computed from the instantaneous cylinder pressure and the piston position. The velocity of the flame front in the combustion charge is an indication of the rate of energy release in the cylinder; both are characteristic parameters of the combustion process. For the present work, pressure and rate of pressure rise will be considered. Provisions are made so that other characteristics of irregular combustion can also be considered.

Pressure and Rate of Pressure Rise

The peak values of pressure and rate of pressure rise and their times of occurrence are fluctuating physical characteristics. Fig. 2 illustrates the fluctuation of both peak values. The correlation between them has to be investigated experimentally, since reasoning does not yield any results because of the many parameters that generate the fluctuation. A prediction of Diesel engine performance based on the calculation of cyclic pressure (14) shows that there is a correlation between peak pressure and peak rate of pressure rise, when the initiation of combustion and the shape of the heat-release diagram are varied. Both Figs. 2 and 3 which represent data I took on a CFR engine also verify the existence of this correlation for a spark ignition engine. If in further investigation the correlation can be shown to be very strong, then it may be sufficient to use only either peak pressure or peak rate of pressure rise as the defining physical characteristics. Similar considerations hold for other physical characteristics, if they can be shown to be dependent on each other.

For the purpose of establishing these relationships, I developed a programmable system capable of measuring selective values of peak pressure, peak rate of pressure rise and of flame front speed.

Synthesis of the System Logic

The principle of the logic design is to correlate measured physical characteristics with measured emissions of individual cycles. Two approaches are possible:

- (a) To collect and analyze exhaust samples for every cycle.

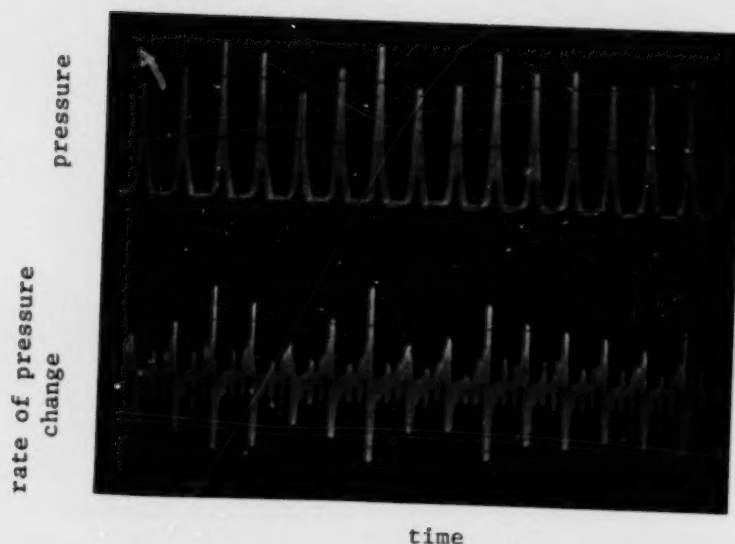


Figure 2. Cylinder pressure and rate of pressure change over a number of cycles

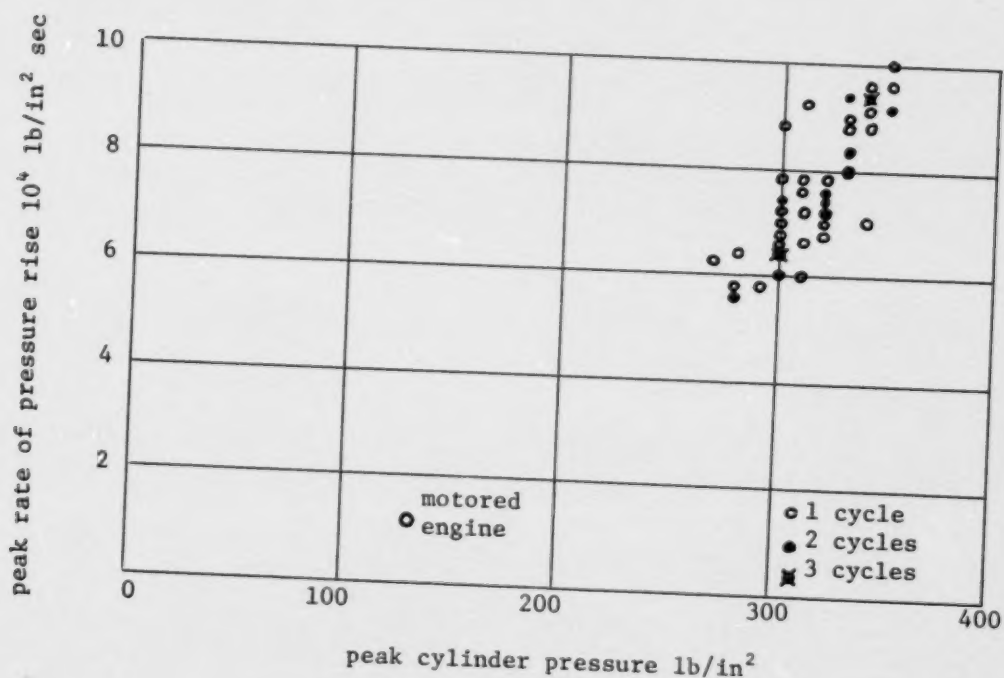


Figure 3. Correlation between peak pressure and peak rate of pressure rise at 900 rpm engine speed

- (b) To collect and analyze exhaust samples for selected similar cycles.

Approach (a) would require a memory for the physical characteristics of each cycle and a high-speed gas sampling or analyzing system that keeps the individual samples separated. This idea sounds appealing because it offers a number of advantages except that the anticipated development problems appeared to be overwhelming. Thus, approach (b) was taken. Here, for each cycle it is necessary to instantaneously determine the physical characteristics under consideration and make a decision on whether or not to take a gas sample from the cycle.

Assuming that cycles with similar physical characteristics have similar exhaust emissions, an accumulation of gas samples from a number of cycles with the same physical characteristics is possible and for the chemical analysis perhaps necessary. For logic decisions based on the occurrence of a certain peak value it will be necessary to establish an interval for the peak value. Similar cycles will be defined as those cycles for which the measured peak values fall within this prescribed interval. The wider this interval, the more samples will be taken in a given time, and the less discriminative will be the sampling.

System Simulation on a Hybrid Computer

In order to study the feasibility of approach (b) explained in the preceding section, the underlying principles of electronic logic and decision making were tested on a digital-control analog computer (Applied Dynamics AD-80). Several ideas were investigated for determining the peak value of a variable represented by a voltage and finding out whether it falls within a preset interval. One was to track the

signal and hold it when its first derivative with respect to time becomes zero, and then compare it with the limits of the interval. This idea could not be used because of the problems connected with differentiation, which will be explained in a later chapter. The simulation on the computer revealed a better technique, which will also be discussed in detail later. In fact, the computer could have been used as part of the final system. Its performance made clear that electronic digital components would have to be used. This was not obvious from the beginning, even if it appears now to be the only possible way.

Chapter III

SYSTEM DESIGN AND FABRICATION

Pressure and Rate of Pressure Change Measurements

It is desirable that signals representing the pressure in the cylinder and the rate of pressure change be available simultaneously. One of the signals can be derived from the other by an integration or differentiation depending on which signal is available first (see Fig. 4). Both electronic integration and differentiation have their difficulties; these will be pointed out later in this chapter. Integration seems to be less of a problem, and a transducer for the rate of pressure change would therefore be of advantage.

An electrodynamic pressure pickup, working on the induction principle with an output voltage proportional to the rate of pressure change is mentioned in Ref. (12). However, this pickup is no longer commercially available. In any case, the frequency response of this type is limited by the natural frequency of its diaphragm. A high natural frequency (by means of a stiff diaphragm) lowers the sensitivity of the transducer; a compromise would be inevitable. Piezoelectric transducers are frequently used in high-speed engine work. Crystalline quartz, when subjected to pressure, shows a separation of electrostatic charges towards opposite ends of the crystal. The size of these charges is proportional to the pressure for a wide pressure range. Although piezoelectric transducers are mainly used to measure pressure it is important to understand that this is not "natural" and that there is no

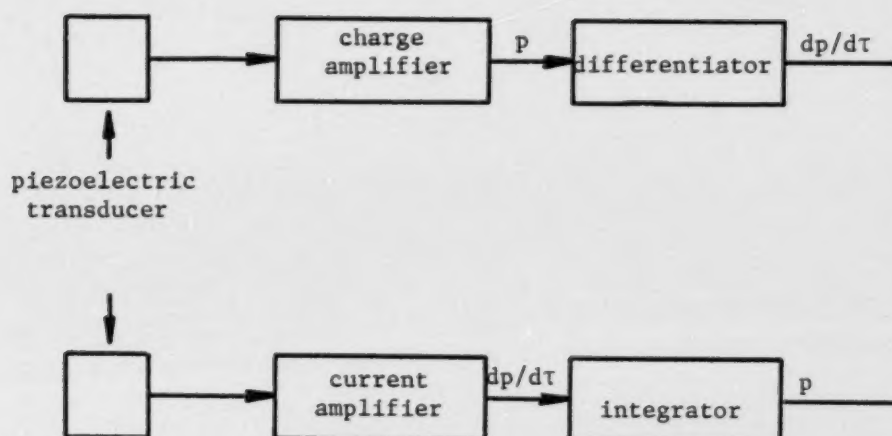


Figure 4. Two configurations for the simultaneous measurement of pressure and rate of pressure change

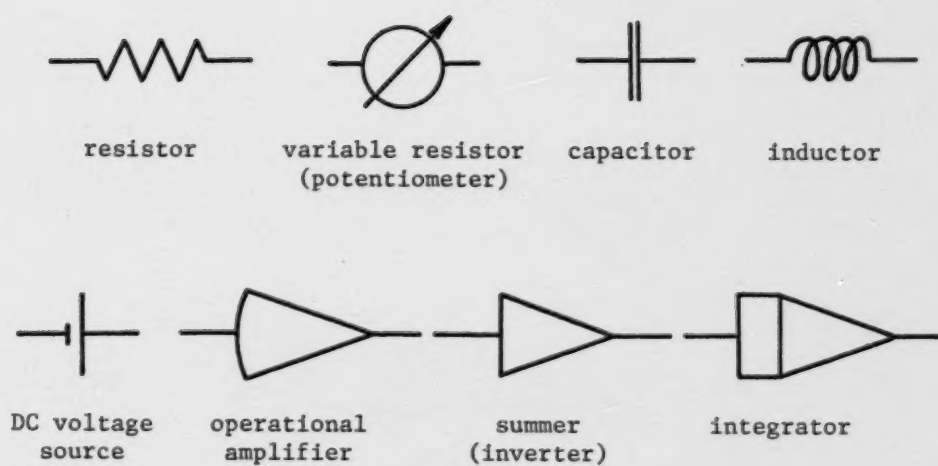


Figure 5. Symbols used in electrical circuits

artificiality introduced by using them to measure the rate of pressure change. The charge results in a voltage signal proportional to the pressure when the two opposite ends of the crystal are electrically connected by means of a capacitor, and in a voltage signal proportional to the rate of pressure change when a resistor is used. Only for completeness it may be added that an inductor results in a voltage signal proportional to the second derivative of pressure with respect of time.

One of the problems in using piezoelectric transducers is that the quartz itself has finite resistance and capacitance which have unwanted and uncontrolled side effects. Any voltage across the quartz results in a leakage of charge and also in a storage of charge in the quartz. By means of an operational amplifier with feedback or some more complicated device the voltage can be kept to a value very close to zero and thus the full amount of charge or current can be subjected to the external capacitor or resistor. The finite impedance of the quartz can then be neglected.

Amplifiers

Symbols used in electrical circuits in this and following sections are explained in Fig. 5.

As was pointed out in the preceding section, the application of pressure on the piezoelectric transducer results in a separation of electrostatic charges. It is a matter of opinion whether one defines the output as proportional to the pressure or proportional to the rate of pressure change; in one case the output is a charge, in the other a current, but in neither case is it a voltage. In order to get a voltage signal, an amplifier has to be used; the term implies here not so much

an amplification of power, but mainly a conversion of one electrical quality into another. If a pressure signal is required, a charge amplifier is to be used; the input is a charge, the output a voltage proportional to pressure. For a rate of pressure change signal, a current amplifier is to be used; here the input is a current, the output a voltage proportional to the rate of pressure change.

The basic difference between a charge amplifier and a current amplifier is (see Fig. 6) that one uses a capacitor in the feedback of an operational amplifier, the other a resistor. The voltages across the feedback loop, which are equal to the output, are proportional to the charge and the current respectively.

Operational Amplifier

The basic component of all amplifiers, integrators, differentiator, etc. is the operational amplifier. Ideally, it has infinite open loop gain at all frequencies. With real operational amplifiers the gain is finite and a function of the frequency. As an example, consider the open loop response shown in Fig. 7a (data taken from Ref. (15) for the operational amplifier that will be used in the integrating circuit). The open loop gain for sine wave signals with frequency f can be written as

$$G = \frac{A}{1+Bj\omega} ; |G| = \frac{A}{\sqrt{1+B^2\omega^2}} \quad (1)$$

and for high frequencies $\omega \gg \frac{1}{B}$,

$$|G| \approx \frac{A}{B\omega} . \quad (2)$$

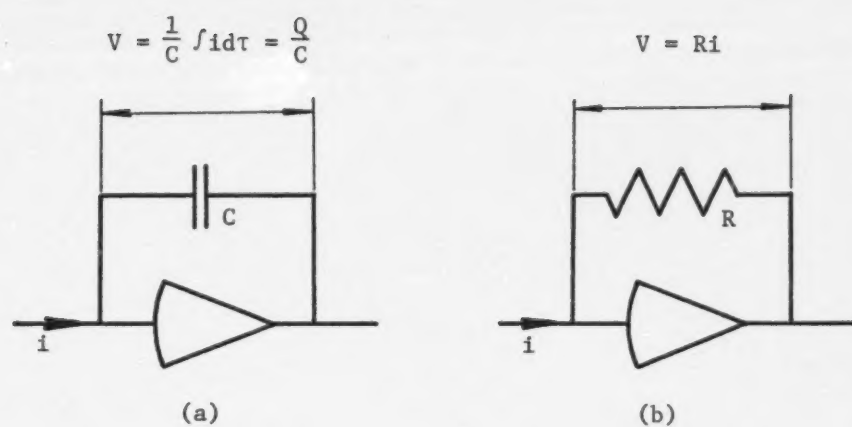


Figure 6. Schematic diagrams of charge amplifier (a) and current amplifier (b)



Figure 7b. Inverter circuit

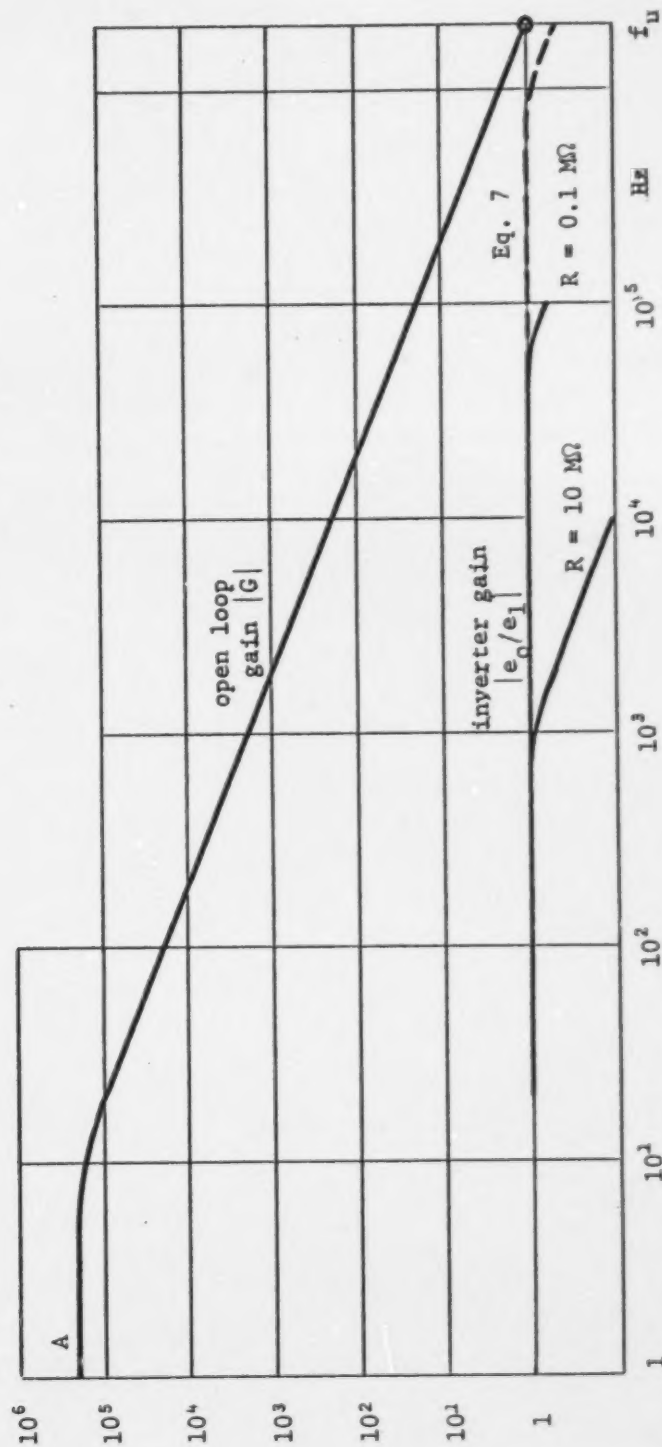


Figure 7a. Open loop gain of an operational amplifier and corresponding gain of the inverter circuit

With a known unity gain bandwidth f_u ,

B can be computed from Eq. (2) as

$$B = \frac{A}{f_u} \quad (3)$$

where A is a function of the amplifier load. Consider next an operational amplifier used in the inverter circuit shown in Fig. 7b.

Neglecting the input current (base current) to the operational amplifier, the current at the summing junction S is

$$i = \frac{e_1 - e_s}{R} = \frac{e_s - e_o}{R} . \quad (4)$$

Together with the definition

$$G = \frac{e_o}{e_s} \quad (5)$$

one finds

$$-\frac{e_o}{e_1} = \frac{1}{1 - \frac{2}{G}} \quad (6)$$

Combined with Eqs. 1 and 3, Eq. 6 yields

$$-\frac{e_o}{e_1} \approx \frac{1}{1 - j\frac{2f}{f_u}} , \quad (7)$$

and for high frequencies

$$\left| \frac{e_o}{e_1} \right| = \frac{f_u}{2f} . \quad (8)$$

The breakpoint between "low" and "high" frequencies can be found from Eq. 8 as

$$f_B = \frac{f_u}{2} \quad (9)$$

For the open loop response shown in Fig. 7a where $f_u = 2$ MHz the breakpoint should be at 1 MHz. The actual operation of the inverter with $R = 0.1 \text{ M}\Omega$ and $R = 10 \text{ M}\Omega$ resulted in breakpoints at 50 kHz and 1 kHz respectively. The discrepancy between theory and practice is caused by a finite base current that becomes influential for high circuit resistances. For high resistances, high-impedance operational amplifiers will therefore have to be selected, and care has to be taken in the wiring of the circuits to avoid uncontrolled capacitances.

Differentiator

As most research work is concerned with the measurement of pressure, charge amplifiers are readily available commercially. In order to get a signal proportional to the rate of pressure change, an electronic differentiator would have to be used with the charge amplifier. The theory of analog circuitry offers suitable circuits. In practice, however, there is a problem, differentiators are also noise amplifiers. For illustration, consider the following example: To a useful sinusoidal signal of amplitude A and frequency $\omega/2\pi$, a sinusoidal noise signal of amplitude $A/100$ and frequency $100\omega/2\pi$ is superimposed:

$$S = A \sin \omega t + \frac{A}{100} \sin 100 \omega t$$

and

$$\frac{dS}{dt} = \omega A \cos \omega t + \omega A \cos 100\omega t$$

In the differentiated signal, the amplitudes of both the useful and the noise signal are equal, namely ωA . This example is realistic; noise signals always have a high frequency, and hence can render a useless differentiated signal. Even though electronic differentiators will not be used, a short survey on differentiating circuits is presented:

a) The simplest differentiating circuit consists of a capacitor and a resistor (see Fig. 8a). The current through capacitor C is proportional to the rate of change of the voltage across it. As the same current has to flow through the resistor, the output voltage across it is a function of the time derivative of the input voltage. The problem is that in order to get voltage across the capacitor equal to the input voltage, the voltage at point A has to approach zero. The more accurate the circuit, the smaller the output becomes, which can be represented by the following equation for sinusoidal voltages:

$$V_o = \frac{RC}{1 + j\omega RC} \frac{dV_i}{dt} \quad (10)$$

The denominator of Eq. 10 is shown as a vector in the sketch in Fig. 8a. Its angle relative to the horizontal represents the phase shift between the true differentiated signal and the output of this circuit, its length relative to 1 is the amplitude ratio. In order to keep the error low, ωRC has to be small. If one allows $\omega RC_{\max} = 0.1$ for the highest frequency to be differentiated, and a useful frequency range

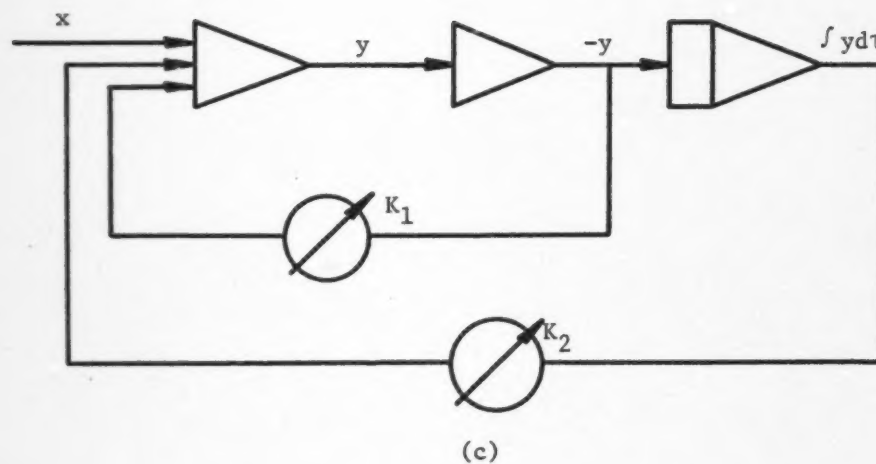
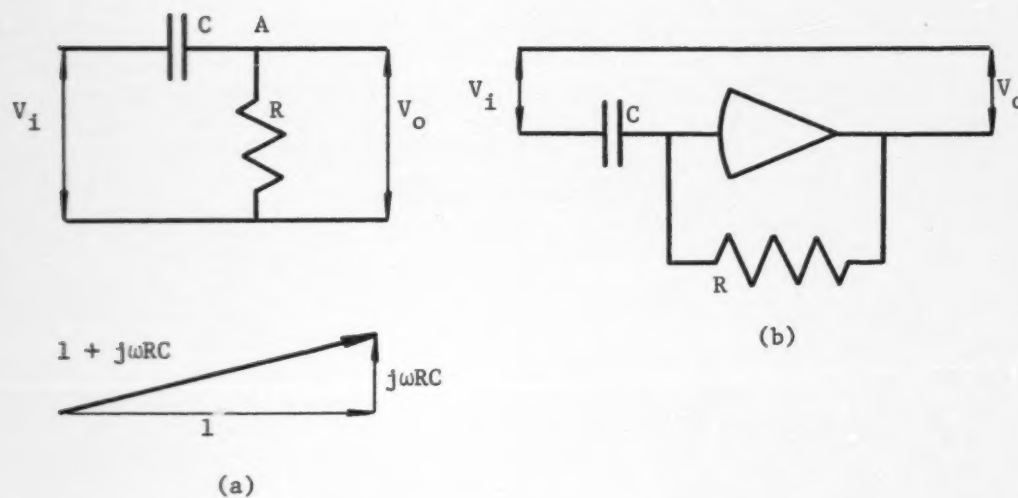


Figure 8. Schematic diagrams of differentiating circuits

$\omega_{\max}/\omega_{\min} = 1000$, then according to Eq. 10 for the lowest frequency which corresponds roughly to the cyclic frequency of the engine the output will only be 1/10,000 of the input. This is not sufficient, because input and output signals should have the same magnitude and a subsequent voltage amplifier is not desirable.

b) A remedy for the problem just pointed out is the use of an operational amplifier, as illustrated in Fig. 8b. However, here the noise problem becomes unsurmountable.

c) Circuits for an approximate differentiation, that avoid the noise problem, have been developed (see, for example, Ref. (13)). One such circuit is shown on Fig. 8c. This circuit represents the differential equation

$$y = -\frac{1}{K_2} \frac{dx}{d\tau} + \frac{K_1 - 1}{K_2} \frac{dy}{d\tau} ; \quad (11)$$

$$\text{when } K_1 \rightarrow 1 \text{ then } y \rightarrow -\frac{1}{K_2} \frac{dx}{d\tau} \quad (12)$$

I checked the circuit on an analog computer. With optimal settings for the values of K_1 and K_2 , the output was noisy for frequencies below 100 Hz and distorted for frequencies above 1600 Hz. Optimization for a wide frequency range is difficult. The circuit is complex, and its differentiating quality depends on a number of variables, among others the frequency characteristics of the operational amplifiers used.

Integrator

As was pointed out above, the alternative to the use of a differentiator for generating pressure and rate of pressure change signals

simultaneously is an integrator. Integrators do not have the high frequency noise problem, but have another problem at the low end of the frequency spectrum. Any input offset (i.e., a DC or low frequency voltage added to the input signal of the integrator), however small it may be, is integrated and after some time results in a noticeable signal in the output. For example, if to a useful periodic signal of amplitude A an input offset of $\frac{A}{100}$ is added, for an integration time constant of 0.01 second the output due to the input offset will reach the value of A in one second. This is a realistic example, and thus the integrator drift problem may in general be no less serious than the noise problem of the differentiator. In this particular case, however, it is possible to keep the integration time short and still have a pressure signal over a long period of time. Periodically in the engine cycle, the cylinder pressure assumes values that are almost perfectly repeated, at least within the accuracy of the pressure measurements. Points during the intake or exhaust stroke or both can be used, where the pressure signal is periodically reset to these fixed values. The integration time is then the time between the resettings. If resetting is done once every revolution, the integration time will be 0.05 second at 1200 rpm. For this short time interval, the input offset can be properly balanced. The position of the resetting switch in the integrator circuit is shown in Fig. 9. Input offset and output drift for an actual engine pressure signal are illustrated in Figs. 10 and 11.

Periodic resetting of the pressure signal without adjustment of the offset results in a saw tooth-like signal, see Fig. 12. Finally, both input signal and adjusted and periodically reset output signal of the integrator are shown in Fig. 13.

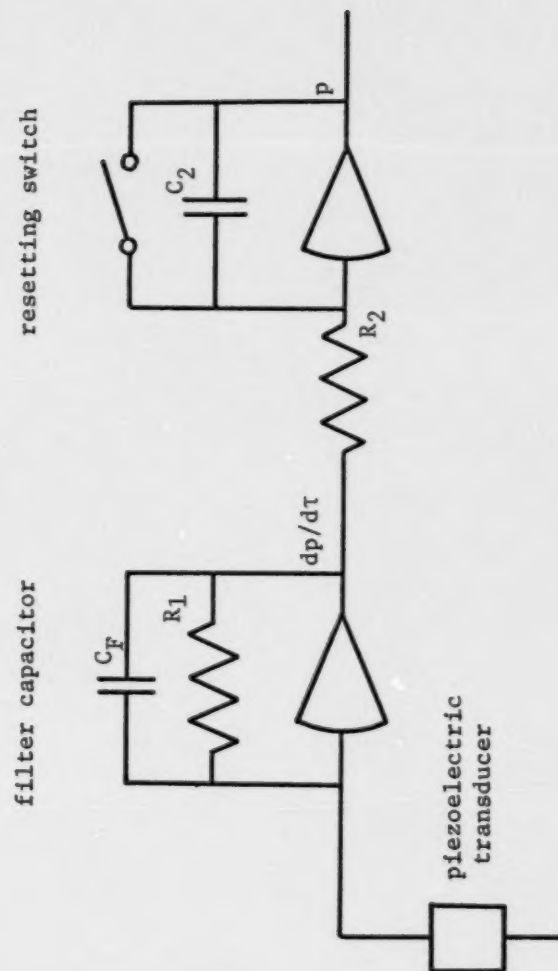


Figure 9. Schematic diagram of analog circuit for measurement of pressure and rate of pressure change

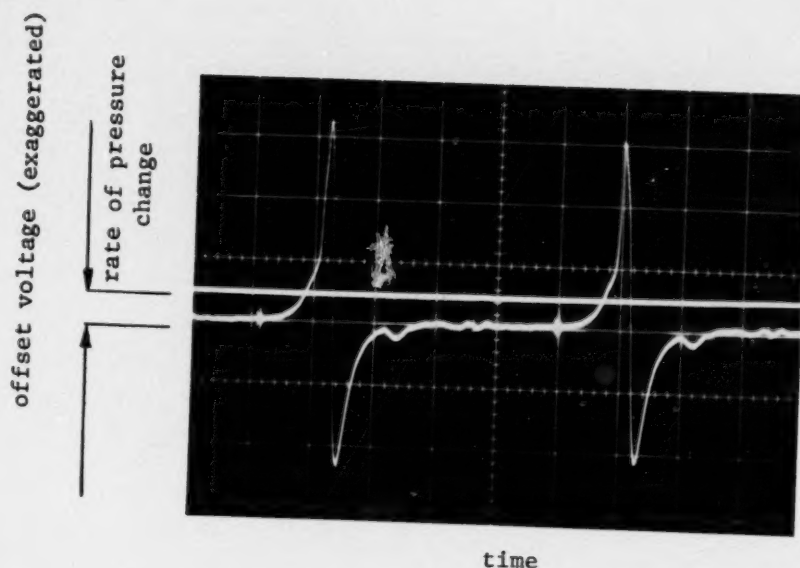


Figure 10. DC offset of integrator input signal (rate of pressure change)

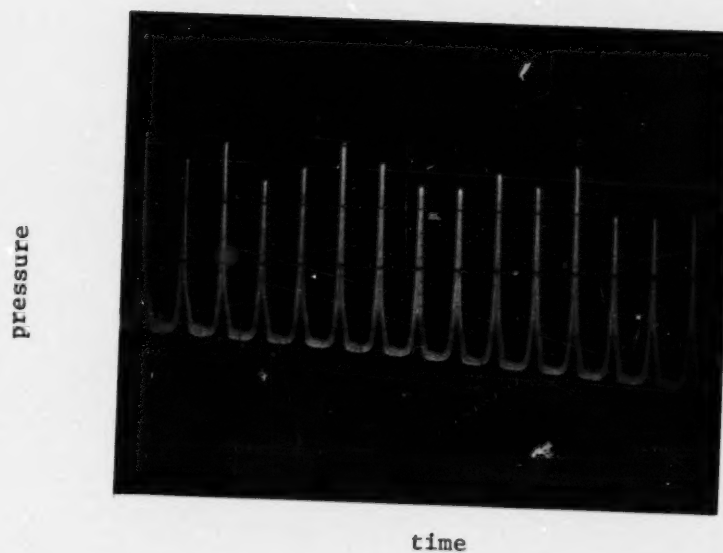
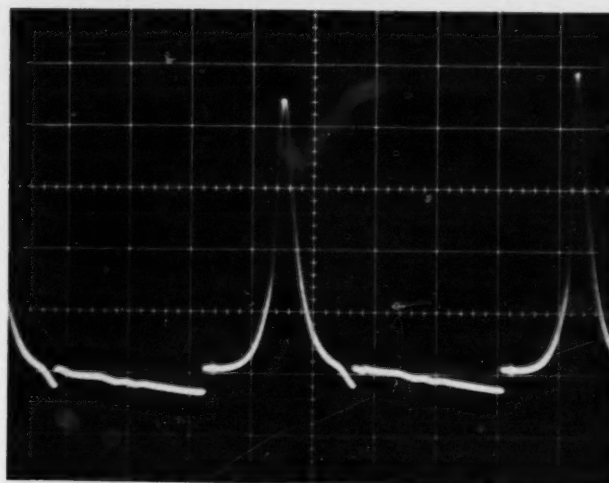


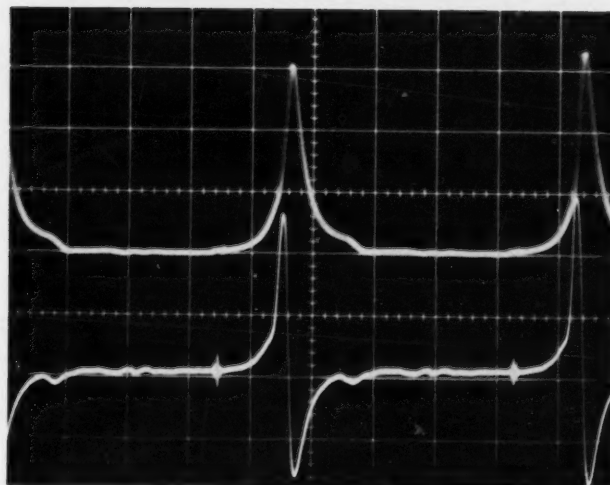
Figure 11. Drift of integrator output signal caused by input offset

cylinder pressure



time

Figure 12. Integrating mode and resetting mode of integrator

rate of
pressure change
pressure

time

Figure 13. Simultaneous pressure and rate of pressure change signals

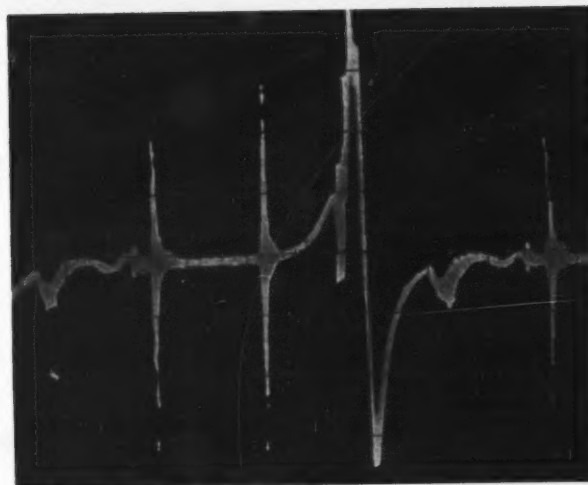
Current Amplifier

Once the decision to use an integrator rather than a differentiator was made, a complementing current amplifier had to be developed. As was shown on Fig. 6b, it consists principally of an operational amplifier with a feedback resistor. For reasons of comparison and versatility I modified a commercially available charge amplifier so that it can now be used as both a current or charge amplifier at a number of sensitivities.

The preliminary operation of the current amplifier together with a piezoelectric transducer resulted in high frequency noise at two distinct points in the cycle, namely when the exhaust and intake valves close. Pictures of the oscilloscope trace (Fig. 14a) show the amplitude of the noise to be of the same order as the useful signal. It seems that the closing of the valves results in a vibration of the cylinder head walls, which is in turn picked up by the transducer due to its acceleration sensitivity. Acceleration-compensated pressure transducers are being developed commercially; here, however, a low-pass filter was used (i.e., a capacitor parallel to the feedback resistor) instead. Comparison of picture (a) with picture (b) on Fig. 14 shows the effect of the low-pass filter. The two pictures are taken from different cycles and therefore are not exactly alike. A computed diagram of the filtering function of the capacitor-resistor combination used in the feedback of the current amplifier is shown in Fig. 15.

Analog Circuit

A schematic diagram of the complete system for the simultaneous measurement of rate of pressure change and pressure appears on Fig. 9.



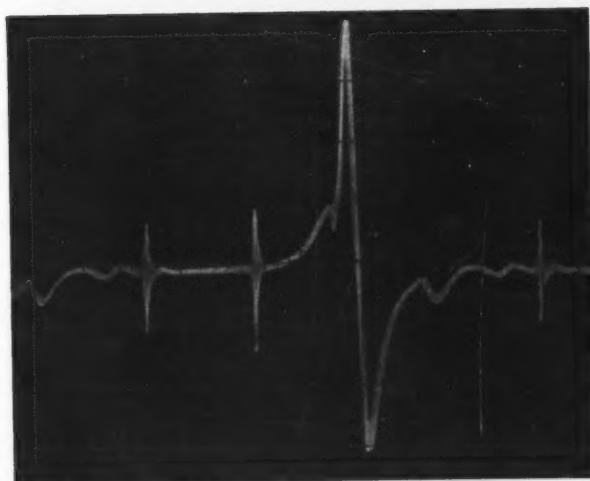
time



intake valve closes

exhaust valve closes

(a)



time

(b)

Figure 14. Rate of pressure change

(a) Unfiltered

(b) Low-pass filter with cut-off at 16,000 Hz

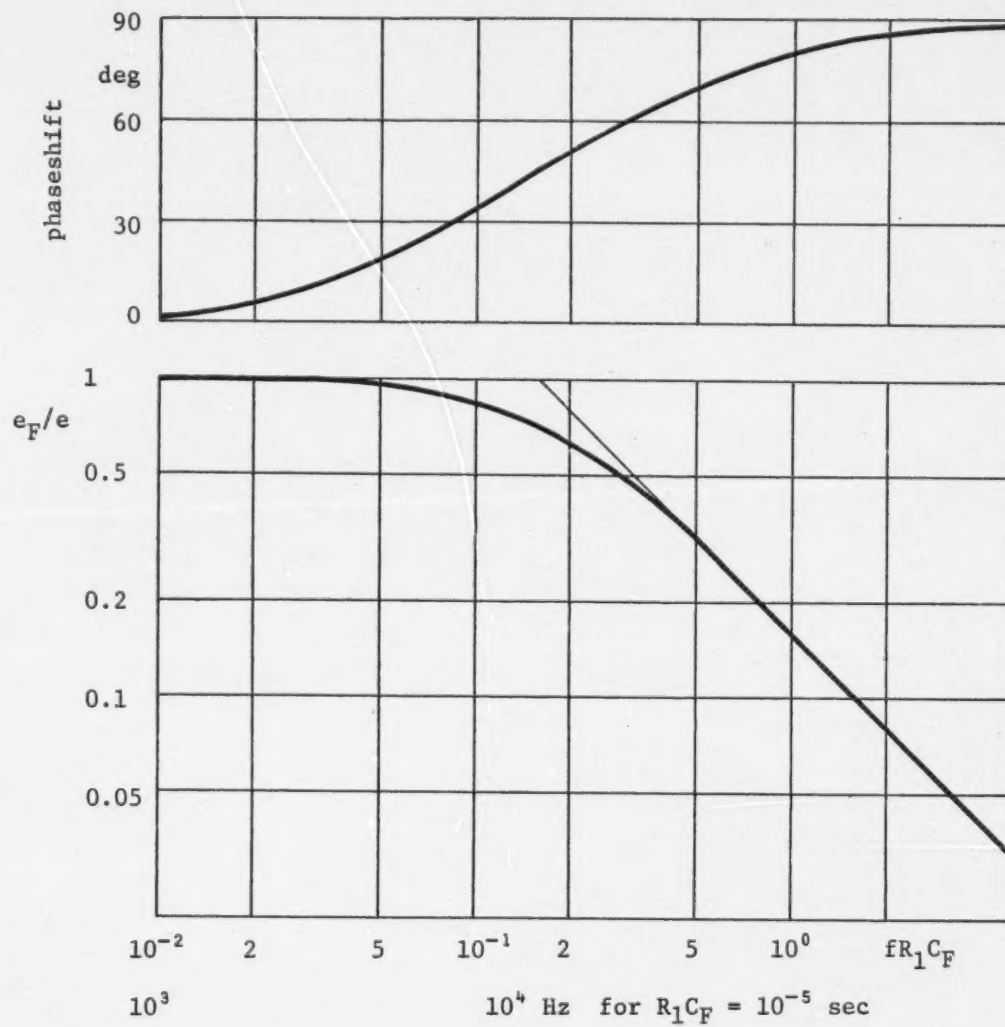


Figure 15. Low-pass filter as feedback for an operational amplifier

The values for the system parameters (resistors and capacitors) are calculated from the expected rate of pressure change and pressure.

Assumed sensitivity of transducer $S = 1\text{p coulomb}/(\text{lb}/\text{in}^2)$

Output voltage range $V = 10\text{v}$

Pressure range $p = 1000 \text{ lb}/\text{in}^2$

Rate of pressure change range $dp/d\tau = 10^6 \text{ lb}/\text{in}^2 - \text{sec}$

$$V = S \cdot dp/d\tau \cdot R_1$$

$$\text{or } R_1 = \frac{V}{S \cdot dp/d\tau} = \frac{10}{10^{-12} \cdot 10^6} = 10\text{M}\Omega$$

$$V = S \cdot p \cdot \frac{R_1}{R_2 C_2}$$

$$\text{or } R_2 C_2 = \frac{S \cdot p \cdot R_1}{V} = \frac{10^{-12} \cdot 10^3 \cdot 10^7}{10} = 10^{-3} \text{ sec}$$

which can be achieved by; e.g, $R_2 = 10\text{k}\Omega$ and $C_2 = 0.1\mu\text{F}$. These values are of course only for orientation; in fact, both current amplifier feedback and integrator input are set up for a number of values in steps of factor 10.

Logic Circuitry

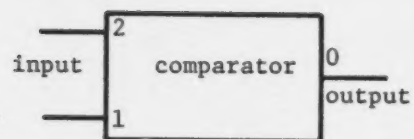
The function of the logic circuitry is to continuously analyze the voltage signals corresponding to physical characteristics of the combustion process. If these input signals fulfill preset conditions (e.g., the peak pressure of a cycle is within a given interval), the output of the logic system will then be a command signal for a sampling valve to take an exhaust gas sample from the cycle under consideration.

Components

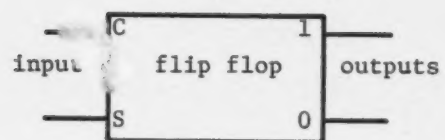
All the components used have binary inputs and outputs (i.e., two logic states represented by two voltage levels), with the exception of the comparators, where the input is a continuous analog voltage. The binary signals may be of the level or of the level change type; for a more detailed discussion see Ref. (16), a handbook edited by the company whose digital components were used. The elements can be divided into three groups according to their "memory": Those where the output depends on the input at any given instance of time (comparator, inverter, gate, relay driver), those where the output depends on some change of the input in past time (flip flop), and those where the output for a preset period of time depends on some change of the input (one shot delay). The symbol code given in the aforementioned handbook is not adhered to here, rather the simplified symbols shown in Fig. 16 are used. As a result, the simplified circuits presented will not correspond to the actual more complicated connections that have to be made on the actual patchboard that is used for the interconnection of all components.

a) Comparator: The logic state of the output 0 changes when the sign of the voltage difference between inputs 1 and 2 changes.

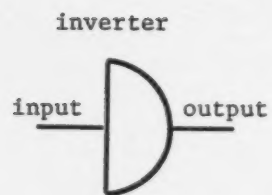
b) Flip Flop: The logic states of the outputs 0 and 1 are complementary (i.e., at opposite voltage levels). Input S is used to set the flip flop, input C to clear it. Both inputs have a built-in delay, which permits a reading of the outputs without ambiguity while the inputs are being changed by a signal partly derived from the same outputs.



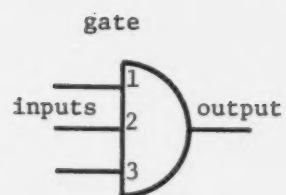
(a)



(b)



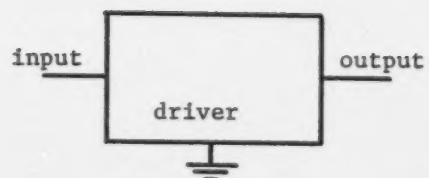
(c)



(d)



(e)



(f)

Figure 16. Simplified symbols for logic components

c) Inverter: The logic state of output 0 is complementary to input 1.

d) Gate: The gates used are NAND gates, which means that only if all inputs are at one logic level will the output be at the other.

e) One Shot Delay: A change in the logic level of input 1 changes the logic level of output 0 for a period of time which can be varied with externally connected capacitors and potentiometers.

f) Driver: For one logic level of input 1 the output 0 is connected to ground, for the other it is open. Thus, the driver can be used as a switch for external loads.

Example of Logic Circuit

The peak pressure discriminating circuit shown in Fig. 17 illustrates the operation of the components. It switches on an external load for a time τ_2 if the peak value of the input signal is within two limits L_1 and L_2 , after a time τ_1 from the point when the lower limit has been exceeded. Four time sequences in Fig. 18 explain the functioning of the components for different input signals.

a) When the peak value is below the interval $L_1 - L_2$, the driver remains disconnected.

b) When the peak value is above the interval $L_1 - L_2$, the driver remains disconnected.

c) When the peak value is within the interval $L_1 - L_2$, the driver is connected. The short pulse in the gate output signal corresponds to the aforementioned delay of the flip flops.

d) If the input signal exceeds the upper limit L_2 only after a time longer than τ_1 counting from the point when it exceeded the limit

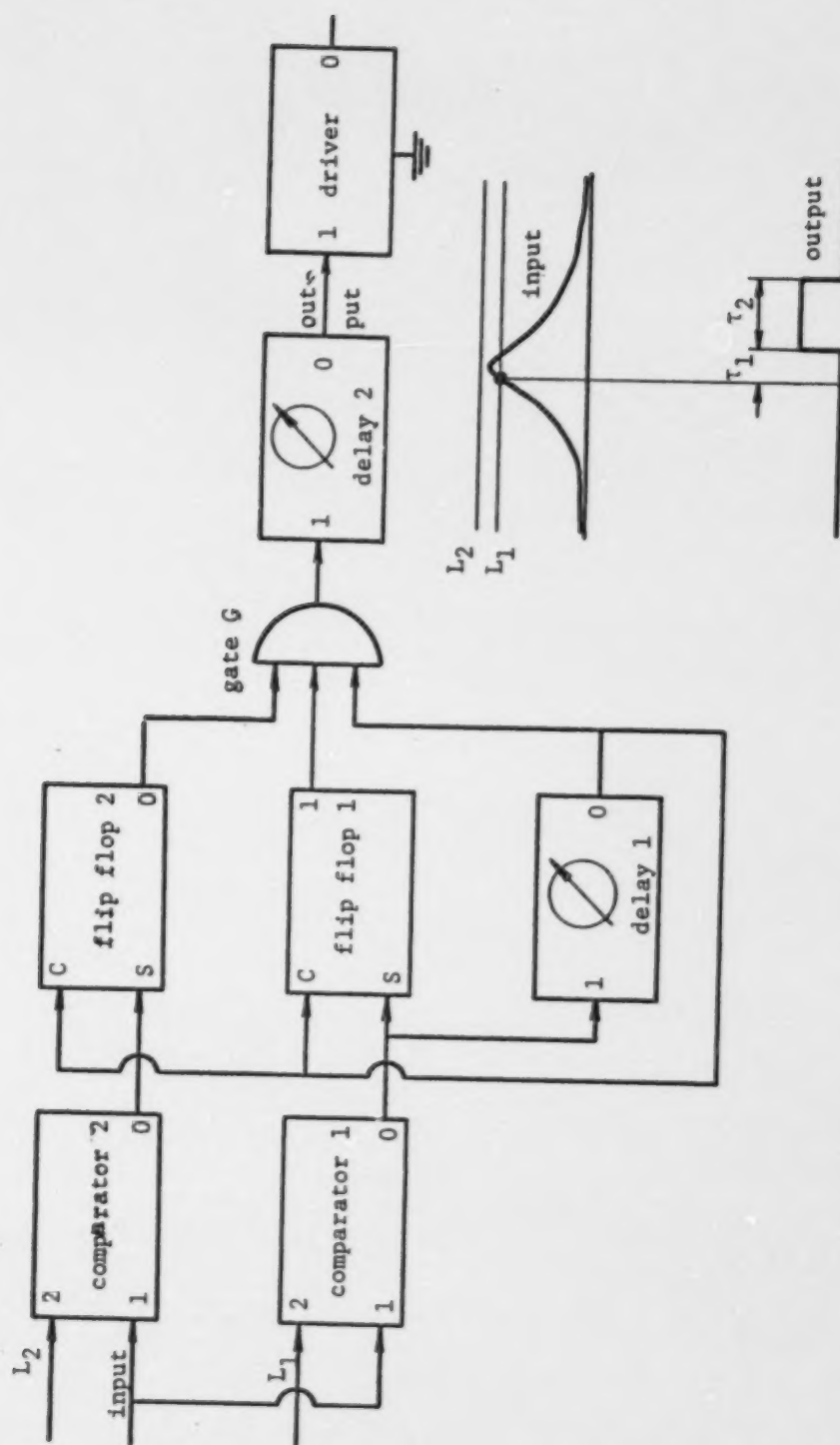


Figure 17. Logic circuit for discriminating peak values

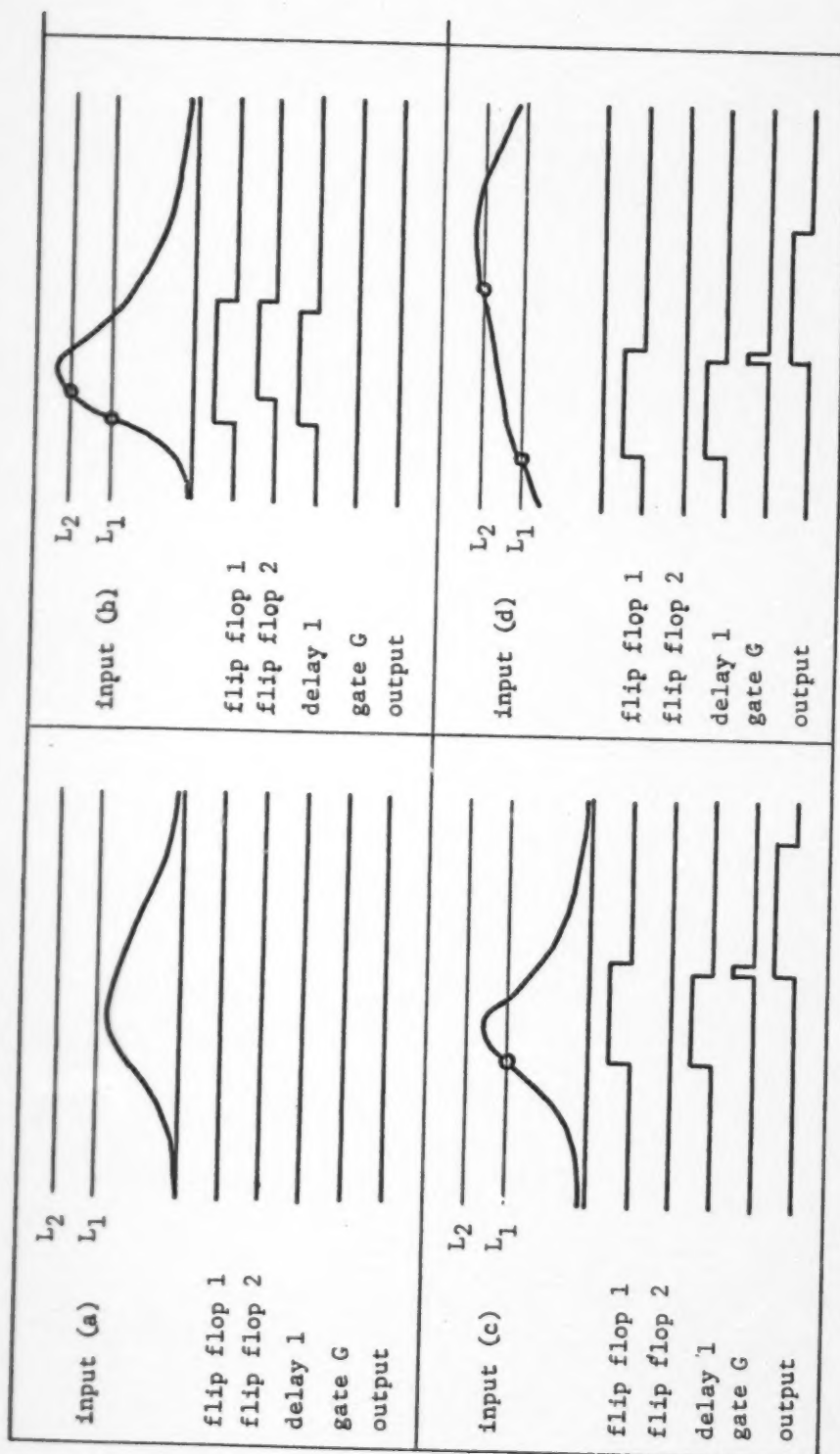


Figure 18. Time sequences for logic states of the components in Fig. 17

L_1 , then the driver will be connected when in reality it should not be. In practical engine work, where the input signals in question have sharp peaks, this situation will not arise. In any case, it can be avoided by an adjustment of τ_1 .

Capabilities of the Logic Circuitry

The system is capable of basing logic decisions on the level (e.g., peak value) or timing and duration (e.g., flame travel time between two points in the cylinder) or any engine characteristics that can be represented by voltages. The logic will handle up to three characteristics which can be analyzed simultaneously and correlated. The results can be used for instantaneous control (e.g., of an exhaust gas sampling valve) and also for statistical purposes.

Sampling Valve

Purpose and Requirements

The sampling valve has to permit a controlled flow of exhaust gas to a collection bag or analyzer. Ideally, it has only two positions, closed and open, which will be controlled in timing and duration by the logic discriminator. The timing has to be adjusted so that if the valve is opened it takes a gas sample only from the combustion cycle in question. For this purpose it is necessary to know the motion of the exhaust gas in the exhaust pipe since the sampling valve is located here (see Fig. 1). Thermocouples mounted in the gas flow proved to be sensitive enough to detect the temperature spike at the front of each new exhaust gas charge as it flows along the exhaust pipe. Correct timing for initiating opening of the sampling valve can therefore be based on gas temperature changes at the valve location in the exhaust

pipe. The valve orifice area has to be evaluated from the requirements of the chemical analyzers. Because continuous flow of sampled exhaust gas is not possible, it may be necessary to collect the samples in bags and analyze them afterwards. If the control signal for the valve can be given approximately 90 deg CA after top dead center and the sampling valve does not have to open before the exhaust valve opens, there are about 90 deg CA or more (depending on the position of the sampling valve downstream in the exhaust pipe) left for the sampling valve to respond. This means about 10 m sec or more response time for the sampling valve at 1200 rpm engine speed.

Design

The short response time required and the electronic control of the valve indicated that electric power would have to be used for the operation of the valve. To prevent excessive inertia forces, the moving masses must be kept as small as possible. Gas pressure forces on the valve should be balanced at all times.

These requirements led to the design of a solenoid-type valve illustrated in Fig. 19. The only moving part is the butterfly, and the static gas pressure on it will be balanced because of the symmetrical design. The steel butterfly is held open by a torsion spring attached to its stem and is closed by the magnetic field of the stator.

The control circuit for the valve is shown in Fig. 20. The stator is powered by a DC voltage supply. When the driver output is disconnected from ground (which breaks the circuit), the closed loop via the diode will protect the driver from the voltage pulse which would otherwise occur.

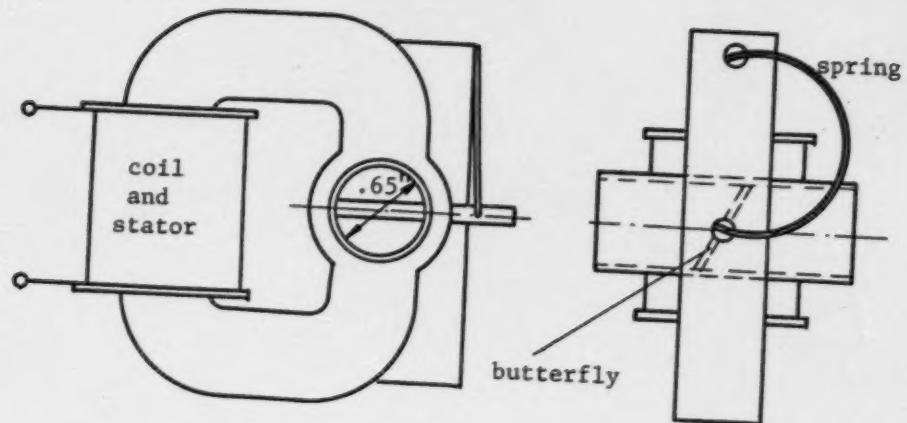


Figure 19. Sampling valve assembly

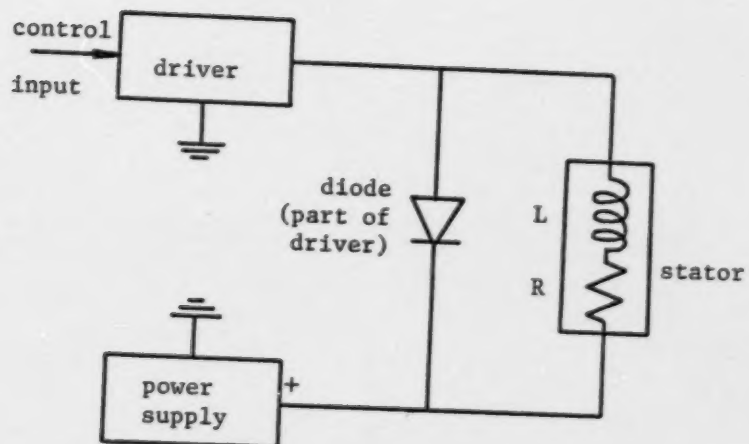


Figure 20. Control and power circuit for sampling valve

Electrical Response

When the power to the solenoid is switched off by disconnecting the driver from ground, the following differential equation holds:

$$Ri + L \frac{di}{d\tau} = 0 \quad (13)$$

$$i = \frac{V}{R} \text{ for } \tau \leq 0$$

which has the solution

$$i = \frac{V}{R} e^{-\frac{R}{L} \tau} \text{ for } \tau > 0 \quad (14)$$

where L = inductance of stator coil = 0.75 h

R = resistance of coil, leads and diode = 100 Ω

V = DC voltage output of the power supply

$$L/R = 7.5 \text{ msec}$$

The term L/R in Eq. 14 represents the time constant for the exponential decay of the current. The magnetic field decays at the same rate because it is assumed proportional to the current. The electrical response of the stator will therefore be partly responsible for a time delay between the switching signal for the circuit and the actual opening and closing of the valve.

It may appear that the time constant L/R could be lowered by means of additional resistors in series with R . This is only partly correct, however, since an additional resistor in series with the diode would defeat the purpose of the diode and thus possibly destroy the driver. For switching on the circuit, an increase of R would not

result in any gain in the time response at all, since for the same steady-state current the supply voltage would have to be increased proportionally, and the decay characteristic would thus be kept constant.

Mechanical Response

Three torques are in balance with the inertia torque of the butterfly; namely, spring torque, magnetic torque and friction torque. For a mechanical analysis of the valve the friction torque is quantitatively neglected. A typical torque-angle relation is plotted in Fig. 21 (spring and magnetic torque are actually opposed to each other). The spring torque is approximately a linear function of the angular position of the butterfly. The magnetic torque assumes the two steady-state characteristics indicated, and during switching (presumably exponential build-up and decay pointed out in the preceding section) all the values in between. The torque that opens or closes the valve will therefore not only be a function of the position of the butterfly, but also a function of time because of the electric response of the stator. This indicates that an analytical treatment will be very difficult; graphical integration would be a way of solution; however, a simplified system yields results of similar accuracy. For this purpose it is assumed that the time needed for the valve to open consist of the time τ_A for the magnetic field torque to decay so that $A = 0$, and the time τ_B during which the butterfly moves to the open position under the influence of only the spring torque.

Using Eq. 14, in which the current has been replaced by the approximately proportional field torque, one finds

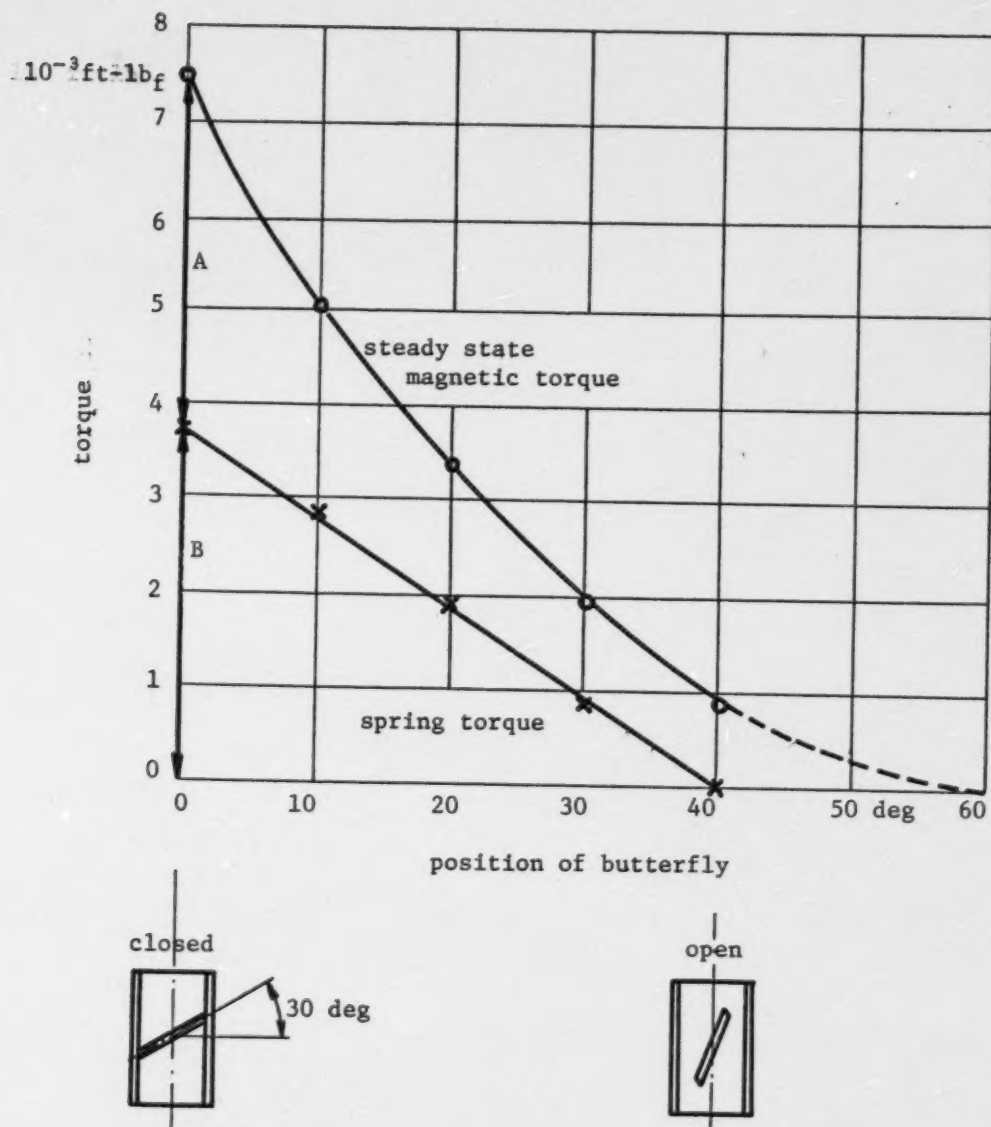


Figure 21. Torques acting on butterfly for 0.2 amp stator current

$$\tau_A = \frac{L}{R} \ln \frac{A+B}{B}$$

and using numerical values, $\tau_A \approx 7.5 \ln 2 \approx 5$ msec.

Neglecting the magnetic field torque from then on, as mentioned above, the motion of the butterfly can be shown to be sinusoidal, and

$$\tau_B = \frac{\pi}{2} \frac{J}{k}$$

where J , the angular inertia of the moving parts is calculated to be

$$3 \cdot 10^{-8} \text{ ft-lb}_f \cdot \text{sec}^2$$

k , the spring constant measured to be

$$5 \cdot 10^{-3} \text{ ft-lb}_f/\text{radian}$$

Using these values, one finds $\tau_B \approx 3.5$ msec which is well reasonable considering the application for which the valve was designed.

Dynamic Testing

For the measurement of the dynamic response of the sampling valve on optical bench as sketched in Fig. 22 was devised. Light from an incandescent bulb passes in a parallel beam through the valve and is focused on a photocell. The resistance of the photocell is a function of the amount of light it receives. Therefore, the voltage output of the bridge circuit in which the photocell forms one leg is a function of the area opened by the butterfly. The calibration of bridge output voltage versus butterfly position is plotted in Fig. 23. Figs. 24a and b show oscilloscope traces of the valve response. The upper trace is

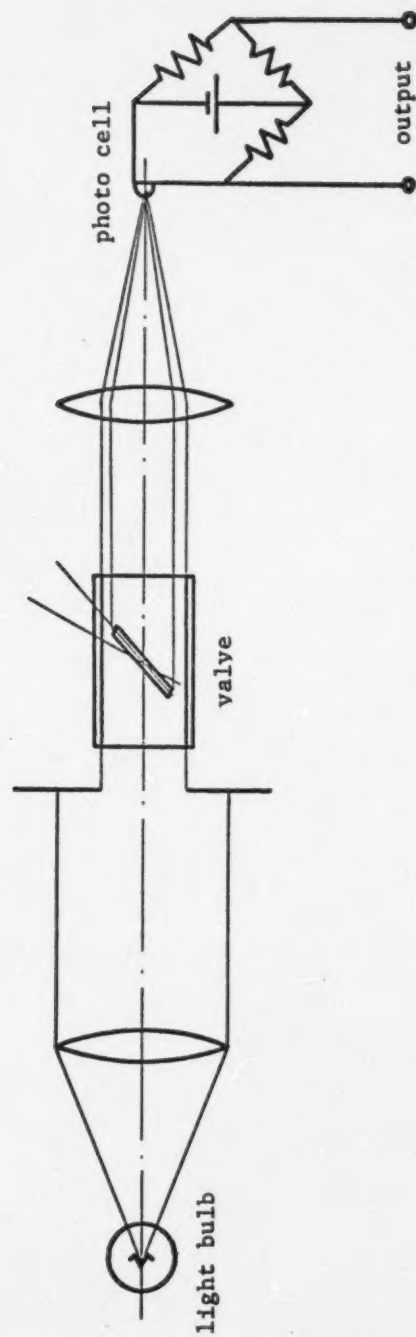


Figure 22. Optical bench for valve response measurement

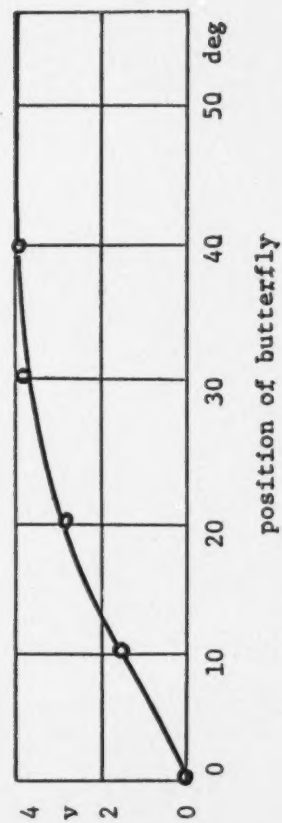


Figure 23. Calibration of optical bench

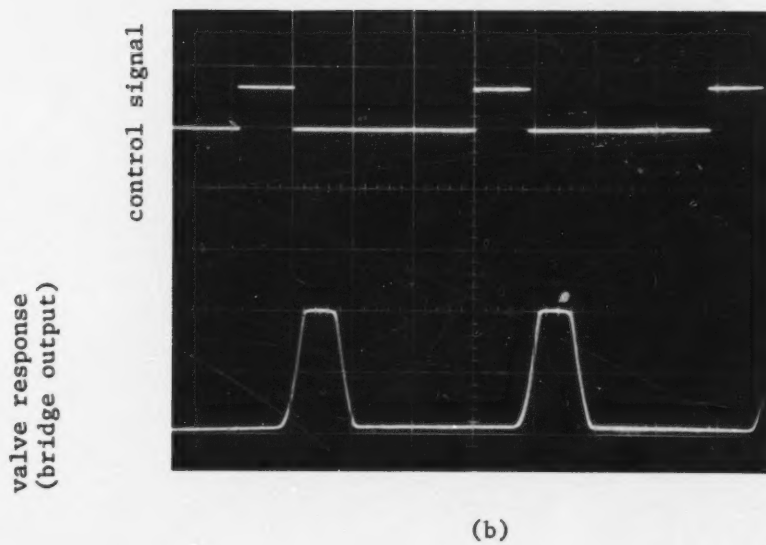
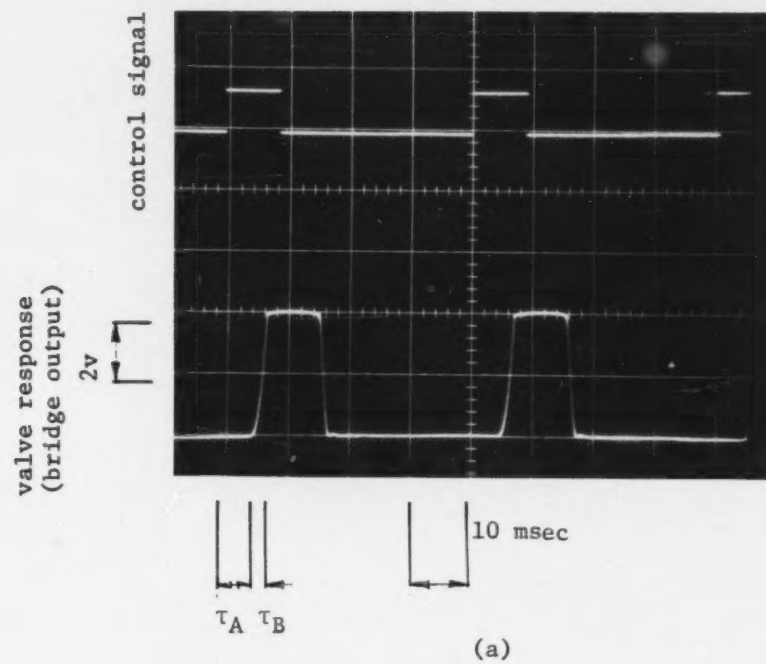


Figure 24. Dynamic response of sampling valve

- (a) 0.2 amp stator current
- (b) 0.15 amp stator current

the signal from the discriminator that controls the driver (see Fig. 17), the lower one is the output of the photocell circuit. The adjustment of the spring is made according to the amperage used. For 0.2 amp stator current the time delay for the beginning of the opening τ_A is about 5 msec, the time for the opening τ_B about 3 msec, as was predicted above. For 0.15 amp, the times are somewhat longer, because a weaker spring was used. In both cases, the duration of sampling was 10 ms. The rectangular top of the valve response curves is partly a result of the low sensitivity of the photometric system beyond thirty degree valve opening.

Leakage

Leakage measurements were made to insure that during the time the valve is closed the amount of gas passing through the valve will be insignificant. Air at a pressure of 3 lb/in² was used for this purpose and the following results were obtained.

Butterfly Position	0	9	18	degree
Air Flow	1.2	17	28	in ³ /sec

The above figures show that when the valve is open the air flow will be more than twenty times greater than when it is closed. This seems to indicate that leakage through the closed valve is small; however, improvement is still possible.

System Synthesis

The complete system consists of the analog circuit for the pressure signals (Fig. 9), a discriminating circuit (Fig. 17) and the power

circuit with the sampling valve (Fig. 20). Through extensive testing the reliability of the system will be fully determined. Such testing will occur as an integral part of the work to be carried out on the project for which this system was designed. In the meantime, a test was run with the valve mounted on the optical bench and using a sine wave signal of a frequency corresponding to 2400 rpm engine speed as an input to the discriminatory circuit. In Fig. 25 the lower trace represents the input sine wave, the upper trace the position of the butterfly as recorded with the optical bench. The amplitude of the sine wave was slowly increased so as to pass through the interval set for the peak value. The valve opens here at peak values between 1 and 2 v in an absolutely repeatable manner, thus fulfilling the requirement that the system itself does not have random fluctuations.

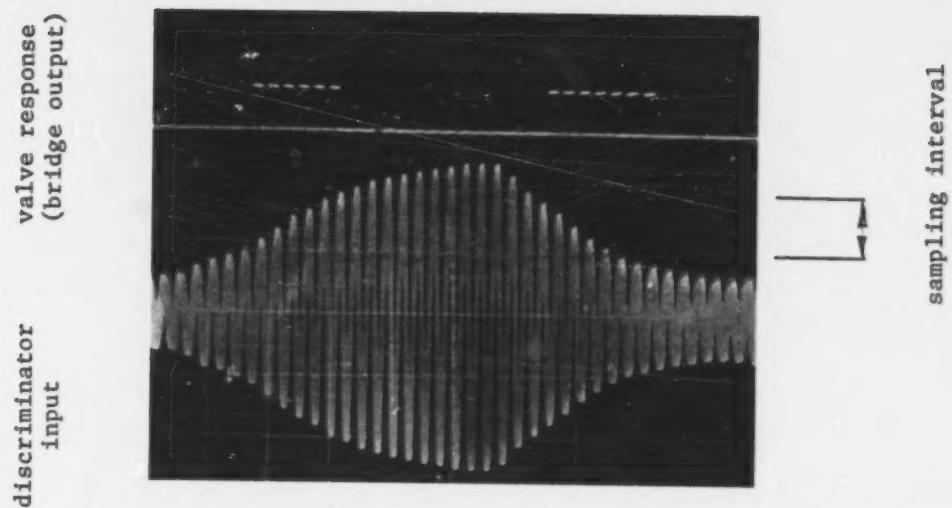


Figure 25. Response of the sampling valve to a sine wave signal as discriminator input

Chapter IV

SUMMARY AND FUTURE WORK

Summary

The recognized cycle-to-cycle irregularity of the combustion process in spark ignition engines has been believed for some time to aggravate the emission of unwanted exhaust gas components. A study of the causes and effects of this irregularity with respect to the physical characteristics of the individual cycle and its exhaust gas composition requires a system that can select exhaust gas samples for chemical analysis. The selection is based on the physical characteristics of the cycles. This system was built and its principles and features are presented here. It consists of:

An analog part for the simultaneous measurement of pressure and rate of pressure change in the cylinder and, eventually, flame travel time;

A logic discriminator that analyzes the analog signals with respect to their timing and magnitude, in particular peak values;

A sampling valve in the exhaust pipe that is controlled by the discriminator.

The system will be used as a tool to aid in the understanding of cycle-to-cycle fluctuations of the combustion process in internal combustion engines. Ultimately then, such understanding could lead to the development of methods for decreasing emissions from these engines.

Recommendations for Future Work

Although all components and the system as a whole are working satisfactorily now, improvements, particularly in the response characteristics, can be made. The use of an acceleration-compensated piezoelectric pressure pickup will suppress the valve-closing noise in the rate of pressure change signal and allow for the use of a current amplifier without low pass filter characteristics. Thus, high frequency components of the pressure signals, particularly for knocking combustion, will be represented more accurately. If the modified charge amplifier now used is replaced by a current amplifier, a high impedance operational amplifier will have to be selected in order not to lose the advantages gained with an acceleration-compensated pressure pickup.

Engine measurements will consist of collecting statistical data for the physical characteristics and of correlating them with the exhaust gas analysis of the combustion cycles. First, under given engine conditions, the distribution of the random physical characteristics will have to be established, thus allowing for a selection of significant physical characteristics and combinations of them. Second, the establishment of the distribution of the cycle-to-cycle emission composition would be desirable; attention has not been given to this area yet. Third, a correlation between physical characteristics and emissions of the combustion cycles should be attempted. Finally, these findings should be a guide to a method of attack on the emission problem of internal combustion engines of the spark ignition type.

REFERENCES

- (1) Vichnievsky, R. "Combustion in Petrol Engines." Proceedings Joint Conference on Combustion. London: Institution of Mechanical Engineers, 1955. p. 288.
- (2) Salé, B. and Vichnievsky, R. "Etude de la Combustion sur le Monocylindre I.F.R. Renault C.N.R.S." Paris: Journal de la Société des Ingenieurs de l'Automobile, 1958. Vol. 31, p. 53.
- (3) Soltau, J. P. "Cylinder Pressure Variations in Petrol Engines." Proceedings of the Automobile Division. London: Institution of Mechanical Engineers, 1960-61. 2, p. 99.
- (4) Curry, Shelley. "A Three-Dimensional Study of Flame Propagation in a Spark Ignition Engine." Society of Automotive Engineers Paper 423B, 1962.
- (5) Curry, Shelley. "The Relationship Between Flame Propagation and Pressure Development During Knocking Combustion." Society of Automotive Engineers Paper 647B, January, 1963.
- (6) Harrow, G. A., Orman, P. L. and Toft, G. B. "The Effects of Engine Operating Variables on the Time of Flame Propagation in a Spark Ignition Engine." Journal of the Institute of Petroleum, July, 1963. Vol. 49, 475, p. 204.
- (7) Patterson, D. J. "Cylinder Pressure Variations, a Fundamental Combustion Problem." Society of Automotive Engineers Paper 660129, January, 1966.
- (8) Warren, J. A. and Hinkamp, J. B. "New Instrumentation for Engine Combustion Studies." Society of Automotive Engineers Transactions, 1956. 64, p. 665.
- (9) Karim, G. A. "An Examination of the Nature of the Random Cyclic Pressure Variations in a Spark-Ignition Engine." Journal of the Institute of Petroleum, March, 1967. Vol. 53, 519, p. 112.
- (10) Ohigashi, S., Hamamoto, Y. and Ono, G. "Statistical Method Evaluating Fluctuations of Engine Performance." Munich: FISITA Congress, 1966. Paper A7.
- (11) Brown, W. L. "Methods for Evaluating Requirements and Errors in Cylinder Pressure Measurement." Society of Automotive Engineers Paper 670008, January, 1967.

- (12) Obert, E. F. Internal Combustion Engines. 2nd Edition.
- (13) James, M. L. et al. Analog Computer Simulation of Engineering Systems. International Textbook Company, 1966. p. 69.
- (14) Winkler, G. "Elektronische Berechnung von Druckverlauf und Wirkungsgrad im Verbrennungsmotor." ("Computation of Pressure and Thermal Efficiency in an Internal Combustion Engine.") Diplomarbeit Institut für Verbrennungskraftmaschinen und Kraftfahrzeuge, Technische Hochschule München, November, 1966. Bericht Nr. 247. -
- (15) Philbrick Solid State Operational Amplifiers, Bulletin 6111. Philbrick Researches, 1967.
- (16) Digital Logic Handbook 1968. Digital Equipment Corporation.

APPENDIX

Description of System Components

Analog part: Quartz pressure transducer Kistler SLM 253

Charge amplifier (modified) Kistler 568

Operational amplifier Philbrick EP85AU

Digital part: Modules from Digital Equipment Corporation

Inverter R 107

Gate R 111, R 121

Flip Flop R 202

One Shot Delay R 302

Driver W 061

Comparator W 520

Miscellaneous accessories: Power supplies for analog part, digital part and valve; mounting panels, patch cords, etc. The valve stator is refashioned from a clock motor.

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